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Preliminary Study for the Passive Containment Cooling System Analysis of the Advanced PWR

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Abstract

The passive containment cooling system (PCCS) is one of the main passive safety systems in the advanced pressurized water reactor (APWR), which will utilize natural phenomena to remove the heat released from the reactor to the environment during the postulated design basic accidents for preventing the overpressure of the containment shell. It is significant for the evaluation on PCCS performance in the design by the numerical simulation with the analysis code. In this paper, a new developed containment analysis code with self-reliance intellectual property rights is used to simulate the containment transients of the advanced pressurized water reactor with the PCCS performance during the postulated LOCA. The sensitivity analyses on some concerned factors are performed. The results show that lower initial humidity in the containment, higher initial environment humidity, higher initial containment temperature and environment temperature will cause higher transient pressure peak in containment during the postulated accident.

Keywords: advanced pressurized water reactor; passive containment cooling system; design basic accident;

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1. Introduction

In the 3rd generation advanced pressurized water reactor designs, a series of passive safety systems are adopted, which utilizes natural and passive methods to remove the heat from the reactor to cool the reactor and protect the reactor vessel and containment shell from overpressure.

The passive containment cooling system (PCCS) provide a safety approach to transfer the heat from the inside of the containment to the environment during the postulated event which results in containment heat-up and pressurization, such as loss-of-coolant accident (LOCA) or main steam line break (MSLB). [1]

As the main part of the PCCS operating under the postulated accident conditions, the steel containment is shown in Fig. 1.

The energy released with the water/steam from the reactor system into the containment after the accidents occur. The heat is transferred to the inside surface of the steel containment vessel by convection and condensation of steam and through the steel wall by conduction.

Heat is then transferred from the outside containment surface to the environment by the following ways:

(1) Air enters the inlets located at the upper part of the shield building wall, flows downwards through an annular space (air flow channel between the containment shell and the concrete shield building), and then turns at the bottom of the air baffle. The air is heated by the containment surface to develop into the natural draft. The heated air rises in the annulus and exits the shield building through the chimney located above the containment shell. The air continuously flows into the inlet of the annulus and removes the heat energy out from the outside surface of the steel containment to the atmosphere by convection.

(2) With provisions of spraying water from Passive Containment Cooling Water Storage Tank (PCCWST) driven by gravity in passive means, the thin water film forms on the external surface of the steel shell. The water film is heated and evaporated into the annular space between the steel containment and the air baffle, and some part heat is taken away, which enhances the cooling capacity of the PCCS.

(3) In addition, a part of heat is transferred from the containment shell to the shield building by radiation, but it is not dominant because of the limited containment shell temperature.

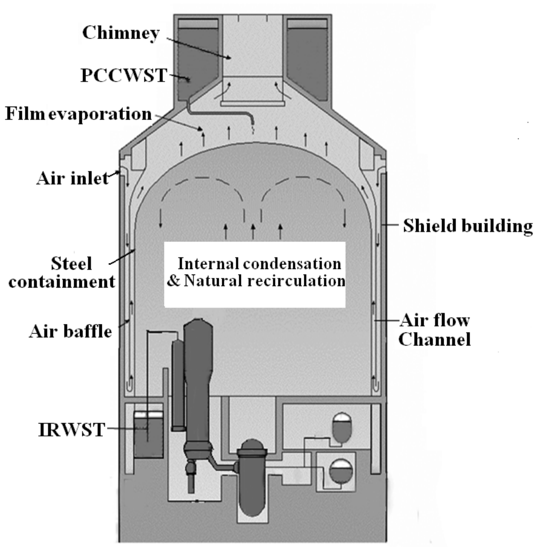

Fig. 1 Illustration of the PCCS

With the above, the passively cooled steel containment utilizes only natural phenomena to remove the energy released from the reactor to avoid the overpressure of the containment during the postulated accidents.

AP1000 is the typical advanced pressurized water reactor designed by Westinghouse Corporation. The pressure in the AP1000 steel containment during the postulated Cold-leg LOCA are calculated by WGOTHIC code. [2] The results indicate the pressure in the containment is limited under the design values and the containment is cooled effectively by the PCCS performance.

2. The codes development for PCCS analysis

2.1. Some existing PCCS analysis codes

Because of the expensive cost of experimental research, numerical simulations were rapidly developed, which had been used in study on nuclear power plant designs and tests. At current, there are several numerical analysis codes on the PCCS performance: some codes, like WGOTHIC[3], CONTEMP4/MOD5[4], COMMIX[5], they are developed from the existing thermal- hydraulic codes to add or modify some models for meeting the key requirements identified by the Phenomena Identification and Ranking Table (PIRT) of PCCS to describe phenomena which govern the PCCS transient.

For the PCCS analysis of the Westinghouse APWR, the thermal-hydraulic code of GOTHIC was selected and modified to Westinghouse-GOTHIC (WGOTHIC) by Westinghouse Corporation with the CLIME model and associated nodding structure combined into GOTHIC to model the special heat and mass transfer in PCCS. The WGOTHIC code was validated by the comparison of the calculated results with the analytical solutions to the specified standard problems and the comparison of the calculated results with the separate effects test data and the integral experimental data for AP600 and AP1000. [1]

2.2. PCCS analysis code development in China

Currently, the large advanced pressurized water reactor of Westinghouse's advanced PWRs is imported, and its technology is mastered and improved. In the future, the advanced PWR with higher power may be designed and constructed in China. Therefore, it is significant to develop the PCCS analysis code with self-owned intellectual property rights.

With the cooperation of State Nuclear Power Technology Research and Development center (SNPTRD) and Tsinghua University in China, the new transient analysis code for the PCCS performance of the large Advanced PWR was being designed [6], which has not the application limitation of the code as the way of developing the code based on the existing codes, and could develop the model in the codes to satisfy the requirements identified from the PIRT of PCCS specially.

The new PCCS code is a muti-dimensional thermal hydraulic analysis code using separated field equations for three phase flow with multiple gas components. The fluids in the containment and in the annular flow channel, constituting of steam, non-condensable air, continuous liquid water and discontinuous water, are considered in the PCCS analysis code.

The PCCS transients during the DBAs for the advanced pressurized water reactor calculated by the new PCCS code were compared with that by the WGOTHIC code. The results show that it has good agreements on the most important pressure transient under LOCA and MSLB accidents, especially on the "pressure peak", which validates the applicability and qualification of the new code on the analysis of PCCS performance.[6]

3. Some analyses on PCCS performance

3.1. Important phenomena for PCCS performance

The performance of PCCS is highly dependent upon the physical phenomena on containment, so it is important to identify the important thermal hydraulic behavior during the transients. With identification and ranking by a PCCS PIRT, the following main heat and mass transfer processes in PCCS are determined:

- Condensation mass transfer inside containment shell
- Evaporation mass transfer outside containment shell
- Convective air flow rate
- Heat conduction in containment shell
- Condensation on internal heat sinks

For the evaluation on PCCS performance, it needs that the analysis codes are available to simulate the transients as mentioned above.

The condensation/evaporation rate is depended on the temperature difference of steam between the water film and the ambient bulk, which can be expressed as a function of the partial pressure difference of steam between the saturated air at the water film surface of the containment shell /internal heat sinks and the ambient air.

The air draft in the annulus space is driven the density difference, which is generated by the temperature differences between the inlets of the containment annulus and the heated outside wall of the steel containment. The physical parameters on air are import parameters for heat transfer by air flow, such as the temperature of the ambient air.

3.2. Sensitivity analyses on containment transient

As the above analysis results from PCCS PIRT, the phenomena during the accident transient are dominant for the effect of the PCCS performance. Therefore, some parameters are selected to have basic sensitivity analyses to evaluate their effect on the containment response for the postulated accidents, such as the initial humidity and temperature in the containment, the initial ambient humidity and temperature, and so on.

In this paper, AP1000 containment is modeled for the PCCS analysis on the postulated design basic accidents of cold-leg LOCA. The mass and energy released from the reactor is calculated by general thermal-hydraulic system code of RELAP5/MOD3.2 and expressed a function of time as the source input. The initial conditions are assumed conservatively as the reference values to maximize the containment pressure peak during the postulated accident. The reference values used in the analysis are listed with Table 1.

Table 1 Reference values of parameters in model

Parameters	Reference value
Initial temperature in containment(℃)	49
Initial pressure in containment(MPa)	0.107
Initial relative humidity in containment (%)	0
Ambient temperature(℃)	46
Ambient pressure(MPa)	0.101
Ambient relative humidity (%)	100
Water film temperature(℃)	49

Initial humidity in containment

Initial humidity affects the initial concentration of noncondensible air inside containment which will reduce the capacity of the steel containment and the internal heat sink structures to transfer and absorb energy by the steam condensation on the surface. The minimum of initial relative humidity in containment (0 percent) is used in the reference evaluation case, which results in a higher peak containment pressure.

The maximum of initial relative humidity (100 percent) is compared with the reference case for the postulated LOCA, in order to quantify the effect of initial containment relative humidity on containment pressure response. The result is illustrated in Fig.2. It shows that the case with 0 percent relative humidity will bring on a higher containment pressure peak than that with 100 percent relative humidity as the above analysis.

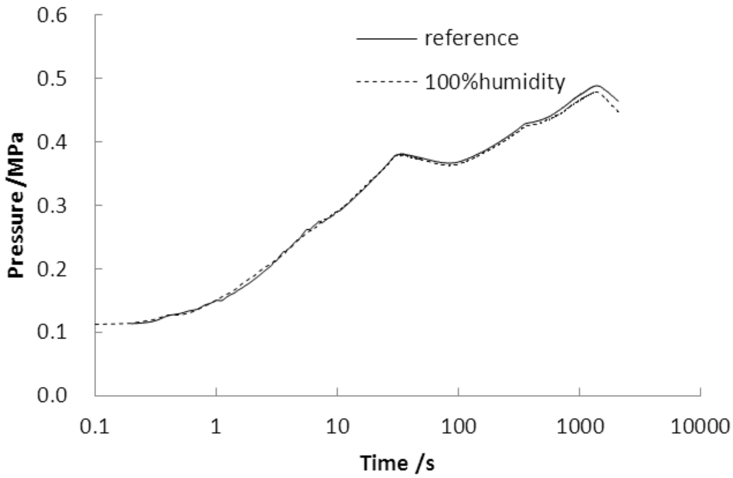

Fig.2 Sensitivity with different initial humidity in containment for LOCA

Initial temperature in containment

The initial temperature is used for the internal heat sinks, the steel containment shell, and air in the containment, which will affect the heat and mass transfer on the internal heat sinks and the steel containment shell, and the heat-absorbing capacity of the structures. A higher initial containment temperature(49℃) is used in the reference evaluation case, and a lower initial ambient temperature of 10℃ is compared with the reference case for the postulated LOCA.

As shown in Fig.3, the pressure with lower containment temperature is a little higher than that in the reference case at the beginning of the accident transient, but the latter exceeds the former gradually and gets the higher pressure peak. It can be explained by that more non-condensable air in the containment with lower initial containment temperature will be dominant to reduce the heat removal capacity at the beginning and the larger heat capacity of the structures in the containment with lower initial containment temperature gets dominant gradually to increase the heat removal of the PCCS.

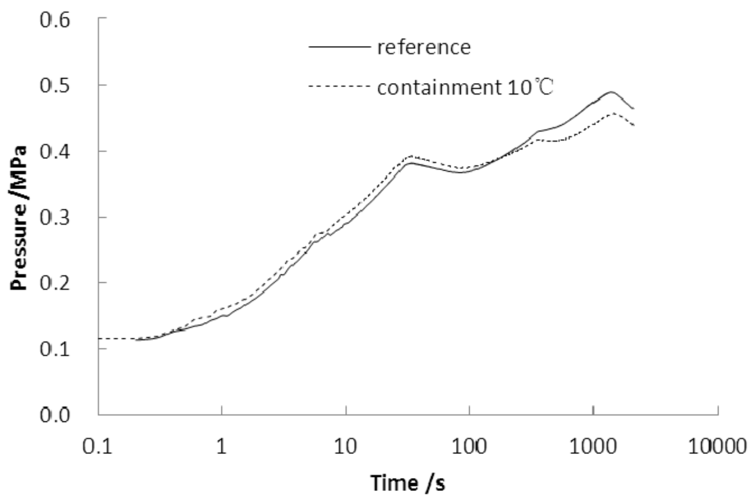

Fig.3 Sensitivity with different initial temperature in containment for LOCA

Initial ambient humidity

The water sprayed from the PCCWST falls and forms thin water film on the outside surface of the containment shell. Evaporation of water film is main way for the heat removal from the reactor during the postulated accident. Evaporation is driven by the concentration gradient, and its rate can be calculated by the steam partial pressure difference between the saturated air at the water film surface and the ambient bulk air in the annulus. Higher relative humidity in the ambient bulk air will increase the steam partial pressure in the ambient bulk air, and reduces the evaporation rate. The maximum of initial ambient relative humidity (100 percent) is used in the reference evaluation case.

The maximum of initial ambient relative humidity (0 percent) is compared with the reference case for the postulated LOCA. The result indicates that the initial ambient relative humidity has no obvious effect on the containment pressure response, and it is not a sensitive factor, as shown in Fig.4.

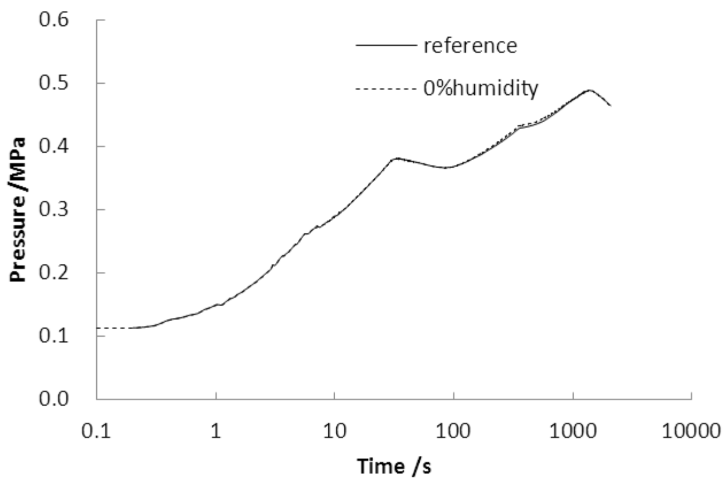

Fig.4 Sensitivity with different initial ambient humidity for LOCA

Initial ambient temperature

Some heat energy is removed out with the flowing-air in the annulus between the steel containment shell and the air baffle by natural and forced convection which is dependent on the heat transfer coefficient and the temperature difference between the water film and the bulk air in the annulus. Obviously, a lower ambient air temperature will result in higher buoyancy for air flow and greater heat transfer capacity. A rather higher initial ambient temperature(46℃) is used in the reference evaluation case.

As shown in Fig.5, a lower initial ambient temperature of 5℃ is compared with the reference case for the postulated LOCA to quantify the effect of initial ambient temperature on containment pressure response. It shows that lower initial ambient temperature will reduce the pressure peak during the postulated LOCA. It has not significant effect, because the ambient temperature perform a function in the convection heat transfer between the containment and the air baffle, which only represents a small contribution in the total energy removal from the containment.

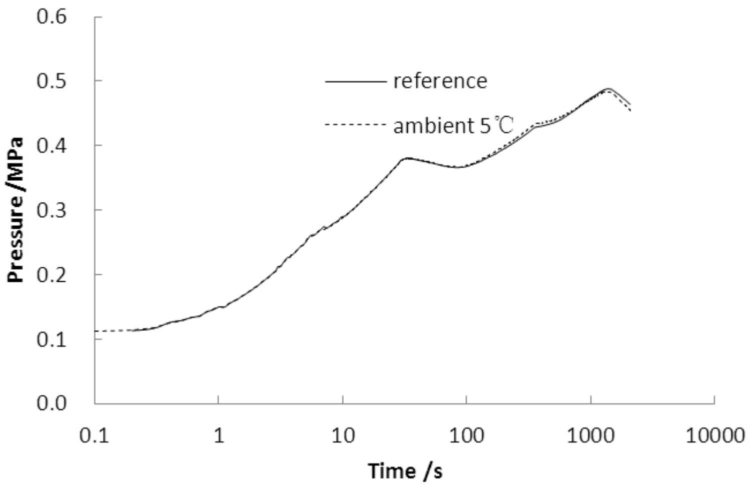

Fig.5 Sensitivity with different initial ambient temperature for LOCA

4. Conclusions

The passive containment cooling system (PCCS) is one of the main passive safety systems in the advanced pressurized water reactor. It is significant to develop the containment analysis code for the evaluation on PCCS performance.

A new PCCS analysis code is developed to simulate the containment transients of the advanced pressurized water reactor during the postulated LOCA. The sensitivity analyses on some concerned factors are performed, such as heat and mass transfer correlation, initial humidity and temperature in containment and environment. The results indicate that lower initial humidity in the containment, higher initial environment humidity, higher initial containment temperature and environment temperature will cause higher transient pressure peak in containment during the postulated accident. The internal parameters in the containment are more sensitive than the ambient parameters for the containment pressure response.

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